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Increasing biological knowledge for better management of by-catch species: age, growth, and mortality of piper and red gurnards (Teleostei: Triglidae)

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Summary: Gurnards are a valuable by-catch of mixed demersal fisheries and are commercially important in European waters, but they are often discarded, reported under "mixed gurnards" and with incomplete biological information by species. In the present work, a total of 558 piper gurnard specimens of between 10.9 and 44.4 cm (1 to 11 years) and 425 red gurnard specimens of between 10.2 and 42.1 cm (0 to 9 years) from the northeast Atlantic (Portuguese) coast were used to study age and growth. The von Bertalanffy growth parameters for piper gurnard were estimated through the combination of whole-otolith readings and back-calculation (L_{∞}=44.7 cm, k=0.16 yr^{-1} and t_0=–2.781 yr). For red gurnard the same growth parameters were estimated using whole-otolith readings (L_{∞}=40.2 cm, k=0.28 yr^{-1} and t_0=–1.074 yr). The results indicate that the red gurnard reaches a smaller length, although it grows faster than the piper gurnard. Natural, instantaneous and fishing mortalities were estimated as well as the exploitation rate for both species. For the Portuguese coast, the red gurnard showed a higher fishing mortality and exploitation rate than the piper gurnard, raising concerns about its sustainable management.

Keywords: by-catch; age determination; growth curves; fishing mortality; longevity; *Chelidonichthys cuculus*; *Trigla lyra*.

Aumentar el conocimiento biológico para una mejor gestión de las especies de captura incidental: edad, crecimiento y mortalidad de garneo y arete (Teleostei: Triglidae)

Resumen: Los rubios son una captura incidental valiosa de las pesquerías demersales mixtas y comercialmente importantes en las aguas europeas, pero a menudo se descartan, se informan como "rubios mixtos" y con información biológica incompleta por especie. En el presente trabajo se han recogido un total de 558 ejemplares de ganeo, de entre 10,9 y 44,4 cm (1 a 11 años), y 425 individuos de arete, de entre 10,2 y 42,1 cm (0 a 9 años) procedentes del Atlántico nororiental (costa portuguesa) se utilizaron para estudiar la edad y el crecimiento. Los parámetros de crecimiento de von Bertalanffy para ganeo se estimaron mediante la combinación de lecturas de otolitos enteros y retrocálculo (L_{∞}=44,7 cm, k=0,16 año^{-1} y t_0=-2,781 años). Para el arete se estimaron los mismos parámetros de crecimiento usando lecturas de otolito entero (L_{∞}=40.2 cm, k=0.28 año^{-1} y t_0=–1.074 año). Los resultados indican que el arete alcanza una talla menor, aunque crece más rápido que el ganeo. Se estimó la mortalidad natural, instantánea y por pesca, así como la tasa de explotación para ambas especies. Para la costa portuguesa, el arete presentó una mortalidad por pesca y una tasa de explotación más altas que el ganeo, lo que generó preocupaciones sobre su gestión sostenible.

Palabras clave: captura incidental; determinación de la edad; curvas de crecimiento; mortalidad por pesca; longevidad; *Chelidonichthys cuculus*; *Trigla lyra.*

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INTRODUCTION

The fishes of the family Triglidae, commonly known as gurnards or sea robins, are medium-sized demersal fishes that are found on soft bottoms in coastal areas up to 500 m depth in all oceans, in both tropical and temperate regions (Hureau 1986, Richards and Jones 2002). Gurnards are commercially important in European waters. In France, they constitute the most important fishery in the western English Channel (ICES Division VIIe), where the market is well established (ICES 2006); in the North Sea, the grey gurnard, *Eutrigla gurnardus* (Linnaeus, 1758) is used for human consumption (ICES 2014); in UK coastal waters especially in the English Channel, gurnards are targeted commercially (Marriott et al. 2010); and in the Mediterranean, tub gurnard, *Chelidonichthys lucerna* (Linnaeus, 1758), streaked gurnard, *Chelidonichthys lastoviza* (Bonnaterre, 1788) and longfin gurnard, *Chelidonichthys obscurus* (Walbaum, 1792) are a valuable by-catch of mixed demersal fisheries (Colloca et al. 2019). When landed, they are mainly reported as "mixed gurnards" making it difficult to interpret official landings, but an average of 3905 t of gurnards were landed yearly between 2010 and 2017 in European Union-28 (Eurostat 2021). In 2010, legislation in the EU changed, requiring gurnards to be landed under their exact species names (ICES 2014). Except for red gurnard, *Chelidonichthys cuculus* (Linnaeus, 1758), for which the precautionary approach was applied and landings were recommended not to exceed 2894 t in 2020 and 2021 in ICES subareas 3-8 (ICES 2019), there is currently no technical measure specific to gurnard species in EU waters, and their exploitation is only subject to the general regulation in the areas where they are caught (ICES 2014). Nevertheless, the increasing interest in gurnards as potential commercial species has promoted the development of monitoring programmes for stock assessment, including the one recommended by ICES for *C. cuculus* within the new Memorandum of Understanding between the European Commission and ICES, aimed at obtaining information on biological parameters (ICES 2006). However, the impact of fishing on gurnard populations has rarely been examined, and studies on key biological parameters and population dynamics used for fisheries management have focused on targeted species, ignoring by-catch or discarded ones, resulting in a lack of biological data and incomplete information about fishing exploitation (Ordines et al. 2014).

This is specifically the case for gurnards off the Portuguese coast, where eight species are caught by the artisanal (mainly polyvalent) and trawler (mainly bottom) fleets: *C. cuculus*, *C. lastoviza*, *C. lucerna*, *C. obscurus*, *E. gurnardus*, large-scaled gurnard, *Lepidotrigla cavillone* (Lacepède, 1801), spiny gurnard, *Lepidotrigla dieuzeidei* Blanc and Hureau 1973, and piper gurnard, *Trigla lyra* Linnaeus, 1758. Gurnards are within the top 25 fish species most landed in Portuguese waters, with an average of 371 t landed per year between 2010 and 2019 (INE and DRGM 2011-2020). Among the four most landed species are *C. cuculus* and *T. lyra* (Rocha et al. 2018). For *C. cuculus*, information available on life-history parameters (age, growth and reproduction), abundance and distribution, length and weight relationships, fisheries data, stock identification and management is scattered in European waters (ICES 2006, Marriott et al. 2010, Ordines et al. 2014). For *T. lyra*, studies on age and growth, length-age composition, reproduction and mortality were published for the Saronikos Gulf (Papaconstantinou 1981) and the Aegean Sea (Papaconstantinou et al. 1992, Ismen et al. 2016).

Key biological parameters routinely used in fisheries to estimate exploitation level (ICES 2018) and still absent from gurnards were analysed in the present study. Therefore, the main goals were (1) to estimate the sex ratio and the weight–length relations, (2) to validate the assignment of age, (3) to model growth, and (4) to estimate mortality and obtain an initial approximation of the exploitation level for *C. cuculus* and *T. lyra* in the coastal waters of western Portugal.

MATERIALS AND METHODS

Sampling

A total of 558 *T. lyra* specimens and 425 *C. cuculus* specimens were collected between July 2018 and December 2019 from commercial fishing vessels operating off mainland Portugal (Peniche, west coast, 39°03′20.4″N, 9°39′54.2″W to 38°00′32.7″N, 8°55′30.7″W; Fig. 1) using trawls, trammel nets, traps and pots. 21 *T. lyra* individuals under 22 cm total length (11.2 cm to 15.3 cm) that are usually rejected on board were directly obtained from fishermen. No *C. cuculus* individuals were collected in June. Total length (TL, to the nearest 0.1 cm) and eviscerated weight (EW, to the nearest 0.01 g) were recorded, and the sagittal otoliths

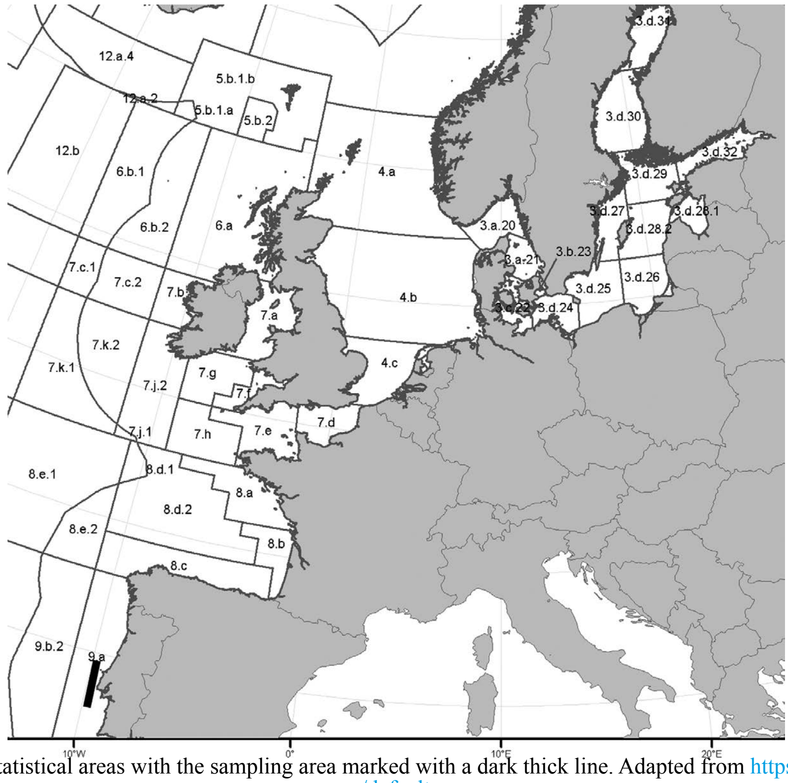

Fig.1 – Map of the ICES statistical areas with the sampling area marked with a dark thick line. Adapted from https://www.ices.dk/data/maps/pages/default.aspx.

were removed, rinsed with water, air-dried and stored in tagged vials. Sex was recorded by macroscopic observation of the gonads. For mortality estimates, the length composition of landings was recorded monthly for each species at Peniche during the study period.

Sex ratio and length-weight relationship

Significant departures from the 1:1 sex ratio were investigated using chi-square tests (Legendre and Legendre 1998). The Mann-Whitney test (*U*) was applied to analyse variation in TL and EW between sexes. The relationship between TL (cm) and EW (g) was calculated using a power function:

$$EW = a\ TL^{b}$$

where *a* is the intercept and *b* is the allometric exponent. Growth allometry between sexes was investigated using the Student *t*-test (Zar 1999).

Ageing methodology and validation

Using a digital camera (DFC 290; Leica, Wetzlar, Germany) coupled to a stereomicroscope (SMZ 745T; Nikon, Kanagawa, Japan), digital images were acquired from whole right sagittal otoliths previously immersed in water with the medial (convex) side down under reflected light and a dark background at 18× magnification. Otolith increment widths were measured along the growth axis from the nucleus to the posterior edge using the "Marking growth rings in fish otoliths" project (https://sils.fnwi.uva.nl/bcb/objectj/examples/otoliths/MD/otoliths.html), for ObjectJ plugin (https://sils.fnwi.uva.nl/bcb/objectj/) of the ImageJ freeware image processing software (National Institute of Mental Health, Bethesda, MD, USA). The posterior edge was chosen because this region has a longer radius and therefore offers better differentiation and individualization of the growth increments (Fig. 2).

The annual periodicity of annulus formation (annual growth increments) was validated semi-directly (Panfili and Morales-Nin 2002) through the analysis of the type of edge and the marginal increment ratio (MIR) (Samamé 1977). The edge of the otoliths was classified as opaque (highly calcified) or translucent (less calcified). The edge type and the mean MIR and standard deviation (SD) were plotted per month to assess annual trends in the formation of growth annuli.

Precision and bias in otolith reading

To evaluate the precision of age assignments and to ensure consistency, representative subsamples of *sagitta* otolith (75 *T. lyra* and 148 *C. cuculus*) covering all length classes and both sexes were read by two authors. Whenever the age estimates did not coincide, a third reading was performed. The average per cent error (APE) (Beamish and Fournier 1981), the coefficient of variation (CV) and the index of precision (D) (Chang 1982) were used to compare age assignments between readers. Bias was evaluated on the basis of age-bias plots (Campana et al. 1995), which help identify departures from the 1:1 equivalence line, and systematic differences in assigned ages between readers were assessed with the Bowker-type test for symme-

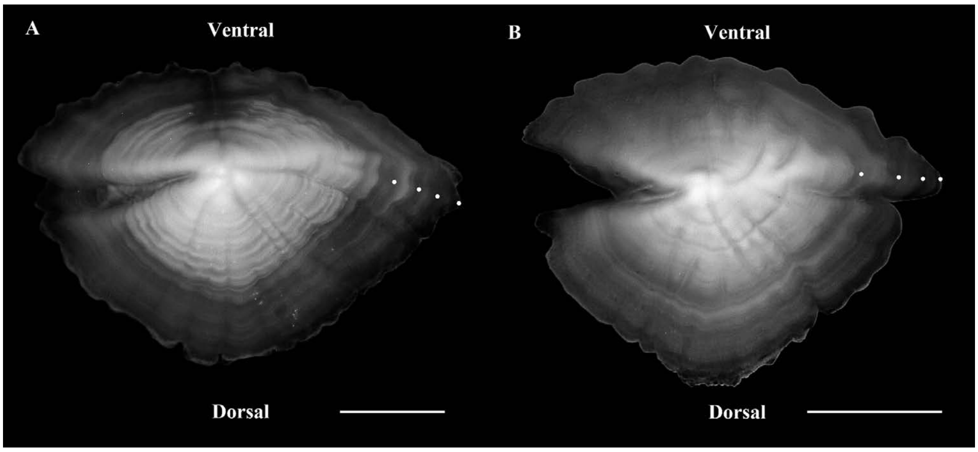

Fig. 2. – *Sagitta* otoliths: A, *Trigla lyra* Linnaeus, 1758, with 29.0 cm TL; B, *Chelidonichthys cuculus* (Linnaeus, 1758), with 29.5 cm TL. Dots indicate annuli. Scale bar: 1 mm.

try (Hoenig et al. 1995) using the FSA package of R (cran.r-project.org) (Ogle 2020).

As there was a good agreement between readers (CV<7.6% and APE<5.5%; Campana 2001), the remaining otoliths were read twice by the first author and readings were used to assign a modal age assuming the 1 January as the birthdate.

Growth model

Because there was a low representation of small individuals (<22 cm) in the sample of *T. lyra*, the von Bertalanffy growth parameters (von Bertalanffy 1938) for this species were estimated using (1) whole-otolith reading, (2) back-calculation (Francis 1990, Jones 2000, Wilson et al. 2009), and (3) a combination of the previous methods (Gordo et al. 2016).

In (1) age was directly estimated for individuals between 10.1 and 44.4 cm. In (2) the mean length-at-age was estimated using a power function between otolith radius (OR) and TL:TL=a OR^b, where a is the intercept and b is the slope (Folkvord and Monsegaard 2002).

In (3) the two previous approaches were used, with back-calculation providing information on length-at-ages 1 and 2 years and whole-otolith readings data for ages 3 to 11 years. The three models were judged using the Akaike information criteria (AIC) (Akaike 1973, Burnham and Anderson 2002). The relative fit of each model was assessed via ΔAIC, with models for which ΔAIC<2 having substantial support and models for which ΔAIC>10 having essentially no support. The model showing the lowest AIC value was chosen as the best approach to estimate the von Bertalanffy growth parameters.

To estimate *C. cuculus* growth, sex-specific length-at-age data based on whole-otolith readings were fitted to the von Bertalanffy growth model (von Bertalanffy 1938). The likelihood ratio tests (Kimura 1980) were used to evaluate the significance of differences in growth parameters between sexes in both species. The growth performance index ($\phi'=\log_{10} K+2 \log_{10} L_\infty$; Munro and Pauly 1983) was used to compare the growth of fish between this and other studies previously published, and the Student *t*-test was used to compare mean ϕ' for the Atlantic and Mediterranean *C. cuculus* populations. Insufficient data precluded this comparison for *T. lyra*.

Analyses were performed in R software (RStudio Team 2020) using the FSA (Ogle 2020) and Rcpp (Eddelbuettel et al. 2020) packages for growth models and the fishmethods package (Nelson 2019) for the likelihood ratio tests.

Mortality

Estimates of mortality for both species were obtained considering only fish caught by trammel nets, the main fishing gear used to capture *T. lyra* and *C. cuculus* in Portuguese waters. The instantaneous total mortality rate (Z, year^{-1}) was estimated based on the age-converted catch curve using the Chapman-Robson mortality estimator (Chapman and Robson 1960) and the first age group as 1 year older than the age of peak (Smith et al. 2012). The instantaneous natural mortality rate (M, year^{-1}) was estimated using Pauly$_{\text{nls-T}}$ estimator (Pauly 1980), M=4.118 $K^{0.73}$ $L_\infty^{-0.33}$ and one-parameter t_{max}, M_{est}=5.109/t_{max} (Then et al. 2015). Fishing mortality (F, year^{-1}) was estimated as $F=Z–M$ and the exploitation rate as $E=F/Z$. Mortalities were estimated using the FSA package of R (Ogle 2020).

All results were considered statistically significant at the 5% level.

RESULTS

Length-weight relationships

A total of 420 females and 138 males of *T. lyra* and 243 females and 182 males of *C. cuculus* were sampled (Table 1). The overall sex ratio (M:F) differed significantly from 1:1 for both species (*T. lyra*, 0.33:1; χ^2=142.52, df=1, P<0.001; *C. cuculus*, 0.75:1; χ^2=8.76, df=1, P<0.05), with females prevailing. Significant differences for TL and EW between sexes and for both species were found (Mann-Whitney test, *T. lyra* TL, U=39905, P<0.001; *T. lyra* EW, U=40528, P<0.001;

Table 1. – Number, total length and eviscerated weight for females and males of *Trigla lyra* and *Chelidonichthys cuculus* collected along the northeast Atlantic (Portuguese) coast. EW, eviscerated weight; N, number of individuals; TL, total length.

	T. lyra		*C. cuculus*	
	Females	Males	Females	Males
N	420	138	243	182
TL range (cm)	11.2–44.4	10.9–41.0	10.2–42.1	13.8–33.4
EW range (g)	15.09–756.92	14.63–679.22	7.83–679.22	19.32–326.09

C. cuculus TL, U=30941, P<0.001; *C. cuculus* EW, U=30316, P<0.001), with females being larger and heavier.

Both species showed a strong relationship between TL and EW expressed by the following equations: *T. lyra* females EW=0.006 $TL^{3.0756}$ (r=0.98, P<0.056, n=420) and males EW=0.006 $TL^{3.0648}$ (r=0.98, P<0.05, n=138); *C. cuculus* females EW=0.006 $TL^{3.1252}$ (r=0.95, P<0.05, n=243) and EW=0.008 $TL^{3.0107}$ (r=0.95, P<0.05, n=182). For both species, there were no significant differences in growth between females and males (paired t-test, *T. lyra* t-test=-0.207, P>0.05; *C. cuculus* t-test=-0.026, P>0.05), and b was not significantly different from 3 in both sexes (paired t-test, *T. lyra* females t-test=2.645, P>0.05; *T. lyra* males t-test=1.190, P>0.05; *C. cuculus* females t-test=0.04, P>0.05; *C. cuculus* males t-test=0.004, P>0.05), indicating that growth was isometric.

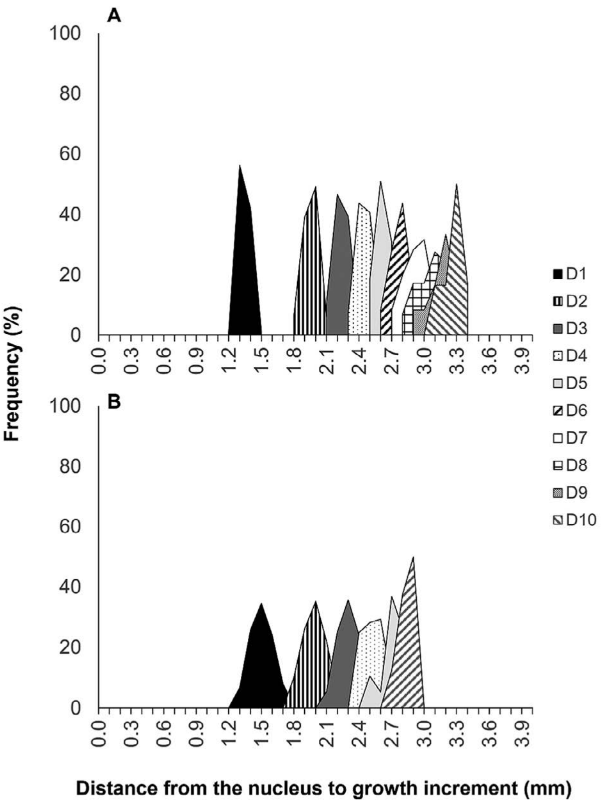

Fig. 3. – Frequency distributions of the distances (D) from the nucleus to the first eight and five growth increments based on the observation of whole otoliths: A, *Trigla lyra* Linnaeus, 1758; B, *Chelidonichthys cuculus* (Linnaeus, 1758).

Ageing method validation

A regular pattern of deposition of annuli was visible in the otoliths of both species, with alternate opaque and translucent concentric increments depositing around an opaque nucleus. Increments were wider close to the nucleus and narrower towards the edge of the otoliths (Fig. 2). False increments were more frequent in *T. lyra*, hindering interpretation.

The deposition patterns of the growth increments showed that the first and second increments were well separated (Fig. 3), particularly in *T. lyra*. From age 3 onwards, separation between increments decreased with age, being more evident for *T. lyra*, which attained greater ages than *C. cuculus*. The distances (mean±SD) from the nucleus to the first ten (*T. lyra*) and six (*C. cuculus*) increments were recorded (supplementary Table S1).

For the analysis of the proportion of opaque and translucent edges and MIRs, 385 otoliths of *T. lyra* (n=385) and 422 of *C. cuculus* (n=422) were used, suggesting similar annual patterns of growth increment formation (Fig. 4): opaque zones occurred more frequently in spring and summer, with MIR tending to increase from May to September, especially for *T. lyra*; translucent edges dominated in autumn and winter, with the lowest values of MIR between October and April, indicating the formation of new increments during this period. Therefore, it is possible to assume that an annual growth increment corresponds to consecutive opaque and translucent growth zones, and age was chosen to be assigned by counting the translucent zones.

Precision and bias in age readings

The indices of precision APE, CV, and D in age assignments between readers for both species are presented in Table 2, and the age-bias plots in Figure S1. There was good precision in age readings, though better results were achieved for *C. cuculus* than for *T. lyra*, with a total agreement of 87% in the former and of 60% in the latter. No evidence of systematic disagreement between readers was obtained for either species (*T. lyra*, χ^2_{R1vsR2}=19, df=5, P>0.05; *C. cuculus*, χ^2_{R1vsR2}=13.10, df=7, P>0.05) indicating simple random error (supplementary Fig. S1).

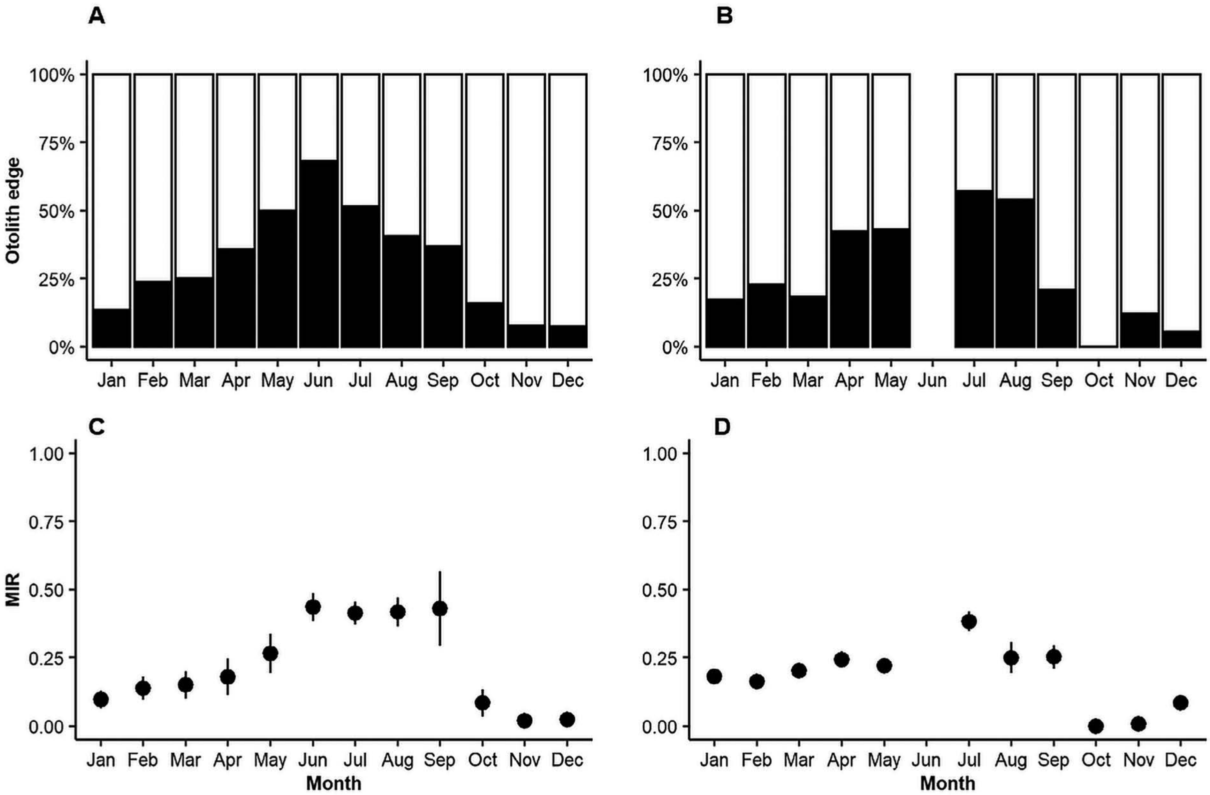

Fig. 4. – Evolution of the proportion of translucent (white bars) and opaque (black bars) otolith edges and the marginal increment ratio (MIR) in whole otoliths: A, C, *Trigla lyra* Linnaeus, 1758; B, D, *Chelidonichthys cuculus* (Linnaeus, 1758).

Table 2. – Indices of precision in age readings of *Trigla lyra* and *Chelidonichthys cuculus* collected along the northeast Atlantic (Portuguese) coast. APE, average percent error; CV, coefficient of variation; D, index of precision.

Indices of precision	*Trigla lyra*	*Chelidonichthys cuculus*
APE (%)	3.943	1.819
CV (%)	5.576	2.573
D (%)	0.200	0.064
Total agreement (%)	60	87
Agreement (0±1) (%)	100	100

Growth models

In total 558 *T. lyra* and 425 *C. cuculus* otoliths were used for ageing. In *T. lyra* age ranged from 1 to 11 years in females and 1 to 10 years in males, and in *C. cuculus* from 0 to 9 years in females and 0 to 5 years in males. The age-length keys obtained from direct otolith reading for both species are shown in supplementary Tables S2 and S3, respectively.

Results for *T. lyra* from the three methods used to estimate the von Bertalanffy growth parameters are shown in Table 3. No significant differences in growth parameters between females and males were found using whole-otolith readings (likelihood ratio test: χ^2=1.09, df=3, P>0.05), and sexes were pooled for subsequent analysis. There was a strong relationship between TL and OR (TL=101.63 $OR^{1.1457}$, r=0.855, P<0.05, n=455). Figure 5A presents the von Bertalanffy growth curves obtained from the three methodologies. According to the AIC, the combined (AIC=40.9) and back-calculation (AIC=43.3) models had substantial support as ΔAIC<2, but as the combined method showed the lowest value it was chosen as the best approach for estimating the growth of this species.

The von Bertalanffy growth parameters estimated for *C. cuculus* are also presented in Table 3. No significant differences between males and females were found (likelihood ratio test: χ^2=1.36, df=3, P>0.05) and sexes were also pooled. The von Bertalanffy growth curve obtained is presented in Figure 5B. Table 3 also summarizes the von Bertalanffy growth parameters and the growth performance indices obtained for oth-

Table 3. – Summary of the von Bertalanffy growth parameters estimated for *Trigla lyra* and *Chelidonichthys cuculus* collected along the northeast Atlantic (Portuguese) coast (this study) and in other geographical areas. A, Atlantic; M, Mediterranean; WO, whole otoliths; BW, burn and whole; CBU, crack and burn; DE, direct estimate; BC, back-calculation; CM, combined method, M, male; F, female; N, number of specimens; L∞, asymptotic length; k, growth rate; t_0, hypothetical age when size is zero; ϕ', growth performance index.

Species	Area	Reference	Reading method	Ageing method	Sex	N	Size [cm]	Age [yr]	L∞ (cm)	K (yr^{-1})	t_0 (yr)	ϕ'
T. lyra	Portuguese coast (A)	This study	WO	DE	All	558	10.9-44.4	1-11	53.7	0.13	-1.918	2.56
T. lyra	Portuguese coast (A)	This study	WO	BC	All	-	-	-	45.9	0.20	-1.134	2.63
T. lyra	Portuguese coast (A)	This study	WO	CM	All	-	-	-	44.7	0.16	-2.781	2.50
T. lyra	Aegean Sea (M)	Papaconstantinou et al., 1992	BW	BC	All	2180	4.3-47.2	0-8	57.4	0.02	-1.245	1.75
T. lyra	Saronikos Gulf (M)	Papaconstantinou, 1981	BW	BC	All	279	4-46	0-7	74.0	0.11	-0.811	2.78
C. cuculus	Portuguese coast (A)	This study	WO	DE	All	425	10.2-42.1	0-9	40.2	0.28	-1.074	2.66
C. cuculus	Western Mediterranean (M)	Ordines et al., 2014	WO	DE	All	873	8-28	0-5	37.6	0.18	-1.825	2.40
C. cuculus	Northwest Wales and eastern Anglesey, UK (A)	Marriott et al., 2010	WO	DE	M	188	15.4-35.0	1-6	41.3	0.21	-1.250	2.55
C. cuculus	Northwest Wales and eastern Anglesey, UK (A)	Marriott et al., 2010	WO	DE	F	552	10-5-43.1	1-7	40.9	0.24	-1.140	2.60
C. cuculus	Northwest Wales and eastern Anglesey, UK (A)	Marriott et al., 2010	WO	DE	All	740	10.5-43.1	1-7	42.4	0.21	-1.210	2.58
C. cuculus	English Channel (A)	Dorel (1986), ICES (2006)	-	DE	M	-	-	1-4	35.6	0.23	-3.370	2.46
C. cuculus	English Channel (A)	Dorel (1986) ICES (2006)	-	DE	F	-	-	1-4	41.1	0.24	-2.570	2.61
C. cuculus	English Channel (A)	Dorel (1986) ICES (2006)	-	DE	All	-	9-43	1-4	36.3	0.24	-0.170	2.50
C. cuculus	Tyrrhenian Sea (M)	Colloca et al., 2003	WO	BC	M	122	7-27 (ALL)	1-3	23.4	0.59	-0.380	2.51
C. cuculus	Tyrrhenian Sea (M)	Colloca et al., 2003	WO	BC	F	127		1-3	24.2	0.74	-0.070	2.64
C. cuculus	Southwest Adriatic Sea (M)	Maisan et al. (1998)	-	DE	M	-	9.5-34.5	1-4	29.3	0.41	-0.490	2.55
C. cuculus	Southwest Adriatic Sea (M)	Maisan et al. (1998)	-	DE	F	-	9.5-34.5	1-5	29.2	0.40	-0.680	2.53
C. cuculus	Gulf of Lion (M)	Campillo (1992)	-	DE	All	-	10-30	1-5	34.9	0.28	-0.660	2.53
C. cuculus	Baie de Douarnenez (A)	Baron (1985)	CBU	DE	M	118	max 50	1-13	37.1	0.51	-0.080	2.85
C. cuculus	Baie de Douarnenez (A)	Baron (1985)	CBU	DE	F	232	max 50	1-21	41.7	0.46	-0.050	2.90
C. cuculus	Aegean Sea (M)	Papaconstantinou (1983)	-	DE	M	507 (all)	4-18	1-5	20.4	0.51	0.008	2.33
C. cuculus	Aegean Sea (M)	Papaconstantinou (1983)	-	DE	F	-	-	1-7	27.6	0.22	0.008	2.22

er geographical areas. Mean ϕ' for the Atlantic and Mediterranean *C. cuculus* populations was significantly different (Atlantic ϕ'=2.677±0.162; Mediterranean ϕ'=2.463±0.136; *t*-test=2.690; df=9.754; $P<0.05$).

Mortality

Estimates of *Z* were 0.61 and 1.67 $year^{-1}$ for *T. lyra* and *C. cuculus*, respectively. Estimates of *M* varied

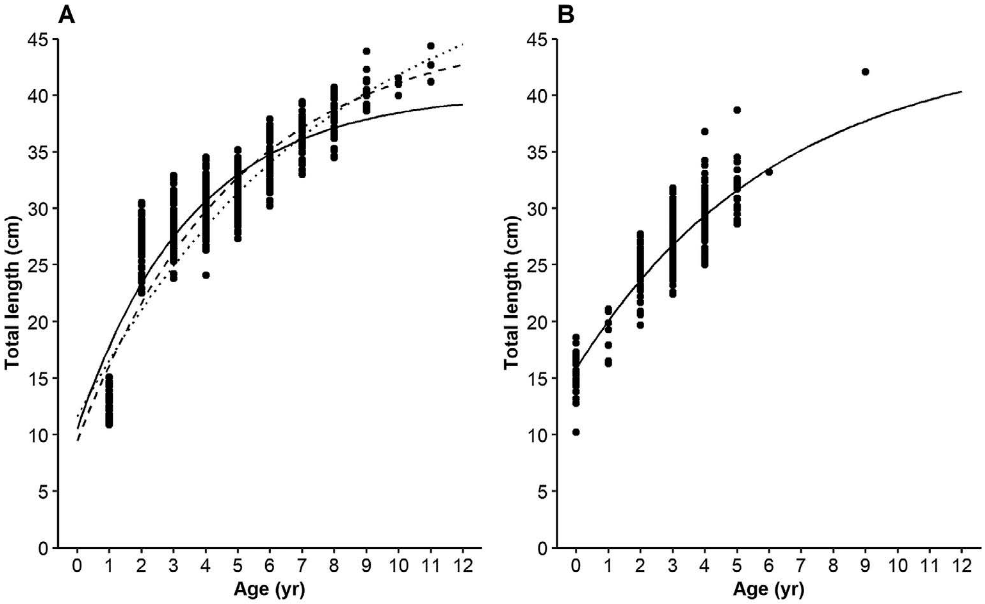

Fig. 5. – The von Bertalanffy growth curves: A, *Trigla lyra* Linnaeus, 1758 (whole-otolith reading, solid line; back-calculation, dotted line; combined method, dashed line); B, *Chelidonichthys cuculus* (Linnaeus, 1758).

Table 4. – Summary of mortality estimators and exploitation rate obtained for *Trigla lyra* and *Chelidonichthys cuculus* collected along the northeast Atlantic (Portuguese) coast. Z, total mortality; M, natural mortality; F, fishing mortality; E, exploitation rate.

	Trigla lyra				*Chelidonichthys cuculus*			
Method	Z (yr^{-1})	M (yr^{-1})	F (yr^{-1})	E (yr^{-1})	Z (yr^{-1})	M (yr^{-1})	F (yr^{-1})	E (yr^{-1})
	0.61				1.67			
$\text{Pauly}_{\text{nls-T}}$		0.31	0.30	0.49		0.48	1.19	0.71
One-parameter t_{max}		0.46	0.14	0.23		0.57	1.11	0.66

with the method used: for *T. lyra*, between 0.31 ($\text{Pauly}_{\text{nls-T}}$ estimator) and 0.46 $year^{-1}$ (one-parameter t_{max}); for *C. cuculus* between 0.48 ($\text{Pauly}_{\text{nls-T}}$ estimator) and 0.57 $year^{-1}$ (one-parameter t_{max}). *F* varied between 0.14 and 0.30 $year^{-1}$ for the former, and between 1.11 and 1.19 $year^{-1}$ for the latter. The exploitation rate (*E*) was higher for *C. cuculus*, ranging between 0.66 and 0.71 $year^{-1}$, while in *T. lyra* it ranged between 0.23 and 0.49 $year^{-1}$ (Table 4).

DISCUSSION

This study presents the first age, growth and mortality characterization for *T. lyra* and *C. cuculus* from the northeast Atlantic (Portuguese) coast, two by-catch species caught by artisanal and trawler fleets. According to ICES (2014), the quality of landings data is poor since the species have usually not been well separated when landed, and updated biological parameters are lacking, particularly for the most important commercial gurnards such as *C. cuculus* (ICES 2006). For a correct stock assessment and sustainable management of fisheries, detailed biological information from all the different species is needed.

Individuals of both species were obtained from commercial fishing vessels using the same fishing gear, but the length range varied between species. Samples of *C. cuculus* included individuals of all length classes between 10 and 43 cm, though most were larger than 23 cm, as expected from landings. Nevertheless, the length distribution gathered from the present study falls within those observed for other European areas (see Table 3). *T. lyra* individuals under 22 cm were underrepresented, and no individuals between 16 and 22 cm were collected from landings; the few individuals gathered were obtained directly from fishermen. This could be related to species-specific ecological features, as they have differeent bottom type preferences, different feeding patterns, a specific depth distribution (Papaconstantinou 1983, Lopez-Lopez et al. 2011) and contrasting reproductive strategies (Neves et al. 2021), which may influence their selectivity in the fishery. According to Lopez-Lopez et al. (2011), on the Galician and Cantabrian Sea continental shelves, mature *T. lyra* over 26 cm are restricted to shallower depths (around 150 m), which is suggested to be related to an ontogenetic shift associated with a change in diet. The fact that individuals under 26 cm are underrepresented in the present study can be related to their higher depth distribution, the size less commercially valued, and the selectivity of the gears regarding the size and the depth where they are used on the Portuguese coast (artisanal gears are used in shallow waters).

Females proved to be more frequent in landings than males for both species in the sample, contrary to findings in the Saronikos Gulf for *T. lyra* (Papaconstantinou 1981) and in the Aegean Sea for *C. cuculus* (Papaconstantinou 1983), where males dominated. Differences in length and weight between sexes were also found, with females being larger and heavier. This is consistent with records for *C. cuculus* in northwest Wales and eastern Anglesey (Marriott et al. 2010), although in the Saronikos Gulf no differences in length between sexes were observed for *T. lyra* (Papaconstantinou 1981).

There were no significant differences in length-weight relationships between males and females, and growth proved to be isometric in both studied species, contrarily to what was found on the south coast of Portugal, where different length-weight relations for both sexes were found, and species showed positive allometric growth (Olim and Borges 2006). This can be related to the lower length range sampled in that study (*C. cuculus*<15.8 cm and *T. lyra*<24 cm) covering mainly juveniles (Ismen et al. 2016, Neves et al. 2021). In other geographic areas, *C. cuculus* showed positive allometric growth with similar length-weight relations between sexes (Olim and Borges 2006, Marriott et al. 2010, Vallisneri et al. 2014). These differences are not unusual and may vary within species depending on the season, population and environmental conditions, which may affect the weight of adults through the maturation of gonads or stomach fullness (Froese 2006). This variation was minimized in the present study by using eviscerated instead of total weight, but it was not possible to account for differences among studies in the length range of individuals.

Edge analysis and MIR validated the annual periodicity of annulus formation in *T. lyra* and *C. cuculus*, which is crucial for age and growth studies. The two age-validation methodologies proved that deposition in both species corresponds to one annulus per year with opaque increments formed in spring/summer. A similar pattern was found for *C. cuculus* in the Aegean Sea (Papaconstantinou 1983) and the Central Tyrrhenian Sea (Colloca et al. 2003) and is likely associated with higher food availability and therefore more energy available for allocation to growth.

In both species, there was a good separation of the first two increments followed by an increasing overlap with distance to the nucleus. This may be associated with energy investment in both growth and reproduction after maturation, leading to narrower annual increments (Wootton 1992). Indeed, length at first maturity estimated for *T. lyra* off the northern Aegean Sea and *C. cuculus* off the Portuguese coast varied between 21.9 and 22.7 cm for males (Ismen et al. 2016) and between 19.9 and 22.1 cm for females (Neves et al. 2021), respectively, which according to the present study should correspond to a maturation age of around two years.

Analysis of precision and bias between readers indicated good consistency for both species, with CV and APE values below the limits suggested by Campana (2001). Nevertheless, *T. lyra* otoliths were more difficult to read than those of *C. cuculus*, with higher values for APE, CV and D and a lower percentage of total agreement between readers. Otoliths of *T. lyra* displayed some discontinuities and false rings, making it more difficult to identify the annuli, especially in larger individuals, which attained older ages than *C. cuculus,* and thus made the ageing process more difficult. But whole otoliths proved to be good structures for evaluating age in these species, without the need for additional treatment, such as burning in *T. lyra* (Papaconstantinou 1981, Papaconstantinou et al. 1992) and crack and burning in *C. cuculus* (Baron 1985). The maximum age estimated was 11 years (TL=44.4 cm) for *T. lyra* and 9 years (TL=42.1 cm) for *C. cuculus*, values that were slightly above those obtained in other studies (Table 3).

To estimate von Bertalanffy growth parameters, different approaches were needed for the two species. The scarcity of young individuals of *T. lyra* precluded the adjustment of the von Bertalanffy equation to the age-length key and justified the use of two additional approaches: the back-calculation method and a combined method (Paiva et al. 2013, Gordo et al. 2016). The combined methodology showed the best adjustment to the data and the most realistic growth parameters.

T. lyra attains a lower TL, and K is naturally higher in this species. Differences in estimated parameters for both species from other European waters were obvious and reflected in different values of ϕ’ (Table 3). *T. lyra* from the Mediterranean showed lower K values, suggesting slower growth rates than in the present study. Results for *C. cuculus* are more difficult to interpret given the data variability among different studies, but the significant difference in mean ϕ’ between the Atlantic and Mediterranean populations suggests that they may have different growth strategies, as already observed by Marriott et al. (2010). Several factors can contribute to these differences, such as the use of different ageing methodologies, sample heterogeneity, different environmental conditions, latitudes and even fishing pressures.

Mortality is an important parameter to understand population dynamics and one of the most influential parameters in stock assessment. Although evaluation of mortality is of great concern among important exploited target species, this does not always happen for by-catch and low-value species such as gurnards. Given the difficulty of estimating M directly and reliably, two estimators based on one and two parameters were used. As expected, some variation was found depending on the method (Then et al. 2015). For the Portuguese coast, *T. lyra* fishing mortality is lower than for *C. cuculus*, also facing a lower exploitation rate. The exploitation rate estimated for northwest Wales and eastern Anglesey (E=0.64 yr^{-1}, Marriott et al. 2010) is similar to those obtained in the present study which, according to Gulland (1971) are considered high because they are over 0.50 yr^{-1}. Species-specific time series with information on length composition in commercial landings could allow us to evaluate the evolution in exploitation rates over time and infer its influence on age composition, which was not possible given the absence of information. On the other hand, these results are in line with those of other studies because the official landings statistics indicate that *C. cuculus* is the second most landed gurnard species on the Portuguese coast (Rocha et al. 2018), justifying the higher fishing mortality and exploitation rate estimated in the present study.

Data on age and growth are essential for the understanding of vital traits of species and populations (Pontual et al. 2002), they are the most frequently used life-history parameters to identify putative stocks (Begg 2005) and, together with mortality, they are important for understanding population dynamics (Ralston and Williams 1988). Although commercially important in European waters, gurnards are mainly by-catch, often discarded, and reported under "mixed gurnards", with incomplete biological and fishing exploitation information by species. The results of this study will contribute to knowledge of the biological parameters of *T. lyra* and *C. cuculus*, helping to define stock characteristics and future management strategies for sustainable exploitation, as recommended by the ICES (ICES 2006). However, additional information on the reproductive strategy of these and other gurnard species and their mixed landings should be obtained for better decision-making in fisheries management.

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SUPPLEMENTARY MATERIAL

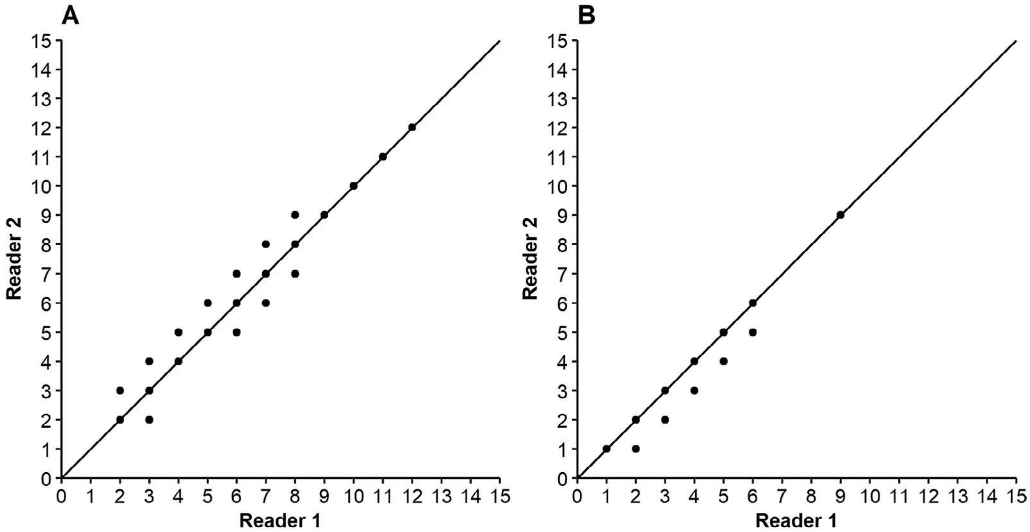

Fig. S1. – Age-bias plots of age assignments from otoliths obtained by independent readers: A, *Trigla lyra* Linnaeus, 1758; B, *Chelidonichthys cuculus* (Linnaeus, 1758). The 45° line represents 100% agreement.

Table S1. – Mean distance from nucleus to each growth increment for *Trigla lyra* and *Chelidonichthys cuculus* collected along the northeast Atlantic (Portuguese) coast.

	Trigla lyra		*Chelidonichthys cuculus*	
	Mean	SD	Mean	SD
D1	1.39	0.04	1.54	0.09
D2	2.01	0.07	2.04	0.09
D3	2.29	0.08	2.38	0.09
D4	2.50	0.08	2.57	0.09
D5	2.68	0.10	2.77	0.05
D6	2.84	0.12	2.95	0.05
D7	2.98	0.12		
D8	3.13	0.17		
D9	3.28	0.22		
D10	3.37	0.33		

SD, standard deviation; Di, growth increments.

Table S2. – Age-length key obtained from direct reading of otoliths of *Trigla lyra* collected along the northeast Atlantic (Portuguese) coast.

Length class (cm)	Age (yr)											Total
	1	2	3	4	5	6	7	8	9	10	11	
10-11	1											1
11-12	5											5
12-13	6											6
13-14	4											4
14-15	4											4
15-16	1											1
16-17												-
17-18												-
18-19												-
19-20												-
20-21												-
21-22												-
22-23		2										2
23-24		4	1									5
24-25		3	1	1								5
25-26		2	3									5
26-27		10	17	3								30
27-28		8	29	12	2							51
28-29		6	32	21	7							66
29-30		4	25	22	14							65
30-31		3	12	26	13	3						57
31-32			6	19	19	5						49
32-33			4	14	13	10						41
33-34				6	13	11	4					34
34-35				2	6	14	5	2				29
35-36					3	7	6	2				18
36-37						11	6	4				21
37-38						4	8	3				15
38-39							4	7	2			13
39-40							2	4	3			9
40-41								6	3	1		10
41-42									2	5	1	8
42-43									1		1	2
43-44									1			1
44-45											1	1
N	21	42	130	126	90	65	35	28	12	6	3	558
TL mean (cm)	12.90	26.86	28.46	30.09	31.40	34.21	36.22	38.06	40.35	41.02	42.77	-
TL SD (cm)	1.29	2.08	1.69	1.90	1.88	1.89	1.73	1.82	1.61	0.55	1.60	-

N, number of individuals; TL mean, mean total length; TL SD, standard deviation of total length.

Table S3. – Age-length key obtained from direct reading of otoliths from *Chelidonichthys cuculus* collected along the northeast Atlantic (Portuguese) coast.

Length class (cm)	Age (yr)										Total
	0	1	2	3	4	5	6	7	8	9	
10-11	1										1
11-12											-
12-13	1										1
13-14	2										2
14-15	5										5
15-16	6										6
16-17	7	3									10
17-18	5	1									6
18-19	2										2
19-20		3	1								4
20-21		1	3								4
21-22		1	2								3
22-23			4	2							6
23-24			11	8							19
24-25			13	37							50
25-26			13	44	7						64
26-27			9	42	10						61
27-28			6	30	7						43
28-29				26	13	2					41
29-30				16	18	3					37
30-31				10	11	3					24
31-32				3	12	3					18
32-33					2	5					7
33-34					3	1	1				5
34-35					1	2					3
36-37					1						1
37-38											-
38-39						1					1
39-40											-
40-41											-
41-42											-
42-43										1	1
N	29	9	62	218	85	20	1	-	-	1	425
TL mean (cm)	15.64	18.69	24.60	26.60	29.18	31.76	33.20	-	-	42.10	-
TL SD (cm)	1.74	1.95	1.85	1.91	2.34	2.36	-	-	-	-	-

N, number of individuals; TL mean, mean total length; TL SD, standard deviation of total length